ENGINEERING CASE LIBRARY

ECL 172A

"THIS MUST BE DONE!" (A)

One morning in early May 1935, the secretary of the Cambridge University Air Squadron handed a private letter to a 28 year old R.A.F. officer taking his Mechanical Sciences Tripos at Cambridge. This letter was to change this man's life and to markedly change the future of aircraft. It was an ordinary looking letter from his friend, R. Dudley Williams, who had been a fellow cadet at Cranwell but had since been retired from the R.A.F. due to ill health.

> *"This is just a hurried note to tell you that I have just met a man who is a bit of a big noise in an engineering concern and to whom I mentioned your invention of an aeroplane, sans propeller as it were, and who is very interested. You told me some time ago that Armstrong's had or were taking it up and if they have broken down or you don't like them, he would, I think, like to handle it. I wonder if you would write and let me know."*

Written by Professor G. Kardos, McMaster University, Hamilton, Ontario, Canada and published with support of the National Science Foundation.

"THIS MUST BE DONE!" (A)

Frank Whittle read his letter, stuffed it into his pocket, and dismissed it from his mind. The last five years of trying to interest the government and industry had completely discouraged him. He had allowed his 1930 patents on the jet engine to lapse in January when it had become due for renewal. The Contracts Directorate of the Air Ministry had informed him that there wasn't sufficient official interest for the ministry to pay the renewal fee of £5 ($25) out of official funds. Whittle was convinced that the engine was "before its time". Because of family problems he could not afford the £5 fee and thus he had allowed the patent to lapse.

Frank Whittle was born in 1907 of Lancashire working class parents. As a youngster Frank helped his father in his small machine shop and acquired much practical experience in manufacturing. In school Whittle scraped through with the least possible effort spending his time pursuing only those subjects which interested him.

At age 20 he joined the Royal Air Force as an aircraft apprentice and received training as an aircraft rigger. At the end of his three years apprenticeship he became one of five to be awarded cadetships to the R.A.F. College at Cranwell due largely to his activities with model aircraft.

During his final year at Cranwell, Whittle was required to write a term thesis. His thesis attempted to predict the trends in aircraft design. B. M. Janes had just published a paper on "The Importance of Streamlining" which showed that at top speed in level flight two thirds of the power of present aircraft, even of a racer, was used in overcoming the drag due to turbulence which could be eliminated by better design of the airframe. Whittle concluded that if this drag could be reduced by streamlining and by flying at higher altitudes, the operational speed of aircraft could be greatly increased. He concluded that to meet future operational requirements aircraft would have to fly higher, faster and further. He was thinking in terms of speeds of 500 miles per hour at 40,000 feet at a time when operational fighters had a speed of 150 miles per hour at 10,000 feet. This led Whittle to consider unconventional means of propulsion. He discussed various power plants and their limitations, piston engine driven propellers, rocket propulsion, and turbine driven propellers.

Completion of the thesis and graduation from the R.A.F. College did not terminate his interest in high speed flight. As a student at the Wittering Flying School he continued his search for a suitable power plant for high speed, high altitude aircraft. He examined jet propulsion using a ducted fan driven by a conventional engine, including the burning of fuel in the outlet nozzle. This arrangement, as far as he could see, had little advantage over the conventional engine-propeller combination.

Toward the end of 1929 it suddenly occurred to Whittle to substitute a gas turbine for the piston engine in his jet. This naturally led him to consider the use of the same compressor for the turbine and the jet. This change meant that the compressor would have to have a much higher pressure ratio than previously considered, in fact, greater than had yet been produced by any blower manufacturer. The idea was so obvious and so simple, Whittle was at a loss to understand why he had not seen it earlier. A series of calculations soon satisfied him that this concept was truly superior to his earlier proposals.

In fact, the use of the exhaust of a gas turbine for jet propulsion had been proposed and patented by a Frenchman, M. Guillaume in 1921. Guillaume's patent was not taken up nor developed and the work was completely unknown to Whittle.

Whittle took his idea to Flying Officer W. E. P. Johnson, a former patent agent. Johnson took Whittle to their commanding officer, Group Captain Baldwin, who was impressed and arranged for a presentation to the Air Ministry. In a few days Whittle found himself at the Air Ministry explaining his ideas to W. L. Tweedie, the director of Scientific Research, and to Dr. A. A. Griffith.

A. A. Griffith was Britain's leading exponent of the gas turbine. Nine years earlier at the Royal Aircraft Establishment he had developed a theory of axial flow compressors and turbines based on the then new theory of airfoils. Griffith believed that he could design a sufficiently efficient gas turbine to make it practical for driving a propeller. In 1926 he proposed and received approval for "preliminary experiments to verify the theory" of an axial flow turbine for aircraft. Griffith's experiments were successful and by 1929 Griffith argued that an aircraft turbine could be built lighter and smaller than current piston engines. His suggestions were considered by the Aeronautical Research Committee, and although it was not recommended for construction, appropriations were made for

further experiments toward that end. Meanwhile, Griffith was transferred to the Air Ministry Laboratory at South Kensington where there were no facilities for such work. It was while at South Kensington that he was called in to assess Frank Whittle's proposals. Thus A. A. Griffith to whom the 22 year old flying cadet made his presentation was one of the foremost authorities on gas turbines in Britain at the time. Griffith later went on to develop the axial flow gas turbine for the Royal Aeronautical Establishment. Eventually at the government's suggestion he was hired by Rolls-Royce to head development of the super chargers for their outstanding Merlin engines.

The results of the meeting were depressing to Whittle. He learned that the Air Ministry did not consider the gas turbine as very practical. Griffith, although enthusiastic about the gas turbine, quietly pointed out certain over-optimistic assumptions and an error in Whittle's calculations that threw his conclusions in doubt.

Discouraged, Whittle returned to his calculations and after carefully revising them found a second error that effectively balanced out the first error so that the conclusions drawn were the same. His confidence in his original conclusions was restored.

The Air Ministry wrote a letter to Whittle pointing out that his proposal was a form of gas turbine, and that its successful development was considered to be impractical, because material did not presently exist capable of withstanding the combination of high stress and high temperature which would be necessary to achieve acceptably high efficiencies. These comments were based upon the Ministry's experience and with the state of the art of gas turbine development. Whittle's proposals at this time were based on thermodynamic and aerodynamic calculations. Outside of the general mechanical arrangement of parts no detail design of turbine elements had been made. Therefore the Air Ministry's comments were correct. No suggestions were made that the proposals would be reconsidered at some future time.

Whittle's case suffered very considerably from his youth, from lack of presence, as well as his lack of technical training and experience. This all made it impossible for him to overcome an opinion universally accepted by the leading engineers and scientists in the field.

At Johnson's urging Whittle filed a patent on his idea in January 1930. In accordance with regulations he informed the Air Ministry of his application. They replied that

there was no official interest in the patent and there was no suggestion of putting the patent on the secret list. Consequently eighteen months later the invention was published and available throughout the world. (Exhibit 1) These and other Whittle patent drawings eventually appeared in a German aeronautical magazine in 1939. (Exhibit 2)

On completion of his training as a flying instructor, Whittle was stationed at Digby Flying Training School. Here he continued developing his idea on the engine. He kept in touch with Johnson who helped him in attempting to interest commercial firms in his ideas. The two young officers when not engaged in their regular duties visited various firms. Many made careful reviews but concluded that, although the principles were sound, they would not be practical for some 10 years. Considering the depressed state of the economy at that time and the high long term investment required the firms could not be expected to do anything about the scheme.

British Thomson-Houston, (BTH), a turbine manufacturer, was one of the firms who showed considerable interest in Whittle's idea. Their chief turbine designer, E. F. Samuelson, and his deputy investigated the scheme thoroughly. They estimated that the development of such an engine would cost £60,000 (approximately $300,000 at that time). They were not prepared to undertake such an investment, especially in the light of their awareness of the technical difficulties of successful gas turbine development and because of its sole application to aircraft which was not BTH field of activity.

Whittle's studies led him to appreciate that his scheme could only be successful if higher efficiencies could be achieved for the various components than were available at the time. He proposed and received patents on improvements on centrifugal compressors. These compressor improvements often took precedent over his jet engine proposals when talking to manufacturers partly because they represented a shorter development and had application in piston engine supercharging and partly because the success of the compressor development would strengthen his case for the jet-engine. This interest in compressors led to a paper on superchargers published in the Journal of the Royal Aeronautical Society and a patent with a fellow officer on the use of an independent engine for driving the supercharger of an aeroengine. Whittle's turbojet proposal required a compression ratio of 4:1 at an efficiency of 75%. The best supercharger then available

had a compression ratio of only 2:1 at an efficiency of only 62%.

Transferred to Felixstowe, Whittle was engaged as an experimental test pilot. Here his ideas were a frequent topic of conversation among his fellow officers, especially since Whittle was constantly attempting to interest the many manufacturer's representatives who visited the base in his scheme. They christened the jet engine "Whittle's Flaming Touch-hole" and invariably greeted him with "Well, how's the old flaming touch-hole?" It was at Felixstowe that Flying Officer R. Dudley Williams took an interest in the turbo-jet. He tried to help Whittle raise money to obtain American and foreign patents on it.

At this time Whittle collected his ideas on his jet-engine. He demonstrated on paper the increases in efficiency with altitude and showed that low temperatures would be beneficial to the engine's operation. His calculations estimated how range was affected by aircraft drag and altitude. From the beginning he conceived of the jet engine and the aircraft as a single system and recognized that the effectiveness and efficiency of both were interlinked, i.e., the reduction in aerodynamic drag would result in increased engine efficiency.

At Felixstowe, Whittle was involved in development flying in which he not only acted as test pilot but submitted a number of patentable ideas for improvement of the aircraft. As a permanent officer he chose to specialize in engineering. His preliminary examination results at officers engineering school were so outstanding that he was allowed to enter the course at a senior level and finish the course in eighteen months instead of the regular two years. He did so well that the Air Ministry gave special approval to his application for advance training at Cambridge, a discontinued policy of regularly sending selected candidates for the engineering course.

Whittle was a little older than his student contemporaries, but he was to later recall, "I found that it was, in many ways, a big advantage to have gone to the university after several years of practical experience, because I had acquired a strong desire to know the explanation of many of the phenomena I had encountered during this experience. Many items of knowledge which had great practical significance for me must have seemed relatively academic to those who had gone to university direct from school."

With Williams' letter in his hand, Whittle's first instincts were to dismiss the matter because of the lapsed patent. On thinking it over he decided that it might be worth encouraging Williams. Even if nothing came of the turbo-jet, their efforts might be able to provide contacts for some of the other patents that Whittle had in mind.

Shortly thereafter, Whittle met mith Williams and J. C. B. Tinling, another ex-R.A.F. officer. The three came to an arrangement whereby they would attempt to raise financial backing for the turbo-jet development. Whittle explained about the patent lapse but proposed a series of patentable improvements which would strengthen their position. Whittle recognized that he was on shaky ground but it was the only negotiating position they had.

An agreement was arrived at whereby Williams and Tinling would cover further patents and other expenses and would act as Whittle's agents. In return they were each to receive one quarter of any profits realized. Patents were filed on a number of additions and changes to Whittle's basic ideas.

Whittle tried to have changed a standard Air Ministry agreement which gave the government free use of all inventions made by serving officers. Despite the fact that the government showed no interest they refused to consider any change in this requirement.

For a number of months Williams and Tinling were unsuccessful in their attempts to raise capital. In October 1935 they met M. L. Bramson, a well-known independent aeronautical engineer. This caused Whittle some concern. Whittle's awareness of his shaky position as to patent protection and his previous experiences had led to one fundamental policy: under no circumstances were they to go to anyone connected with the aircraft industry.

Bramson introduced them to O. T. Falk and Company, Ltd., an investment company set up by the directors because they were conscious that there was a real national problem growing up in England due to the increasing tendency of investors to seek security above all in their investments. Thus Falk and Partners, although not specialists in financing of new technical developments, were particularly receptive to such ideas, and had already financed a few other blue sky projects.

The man to whom Bramson and Whittle took their ideas was L. L. Whyte, a leading partner in the firm. Whyte was unusually well equipped to take an interest; he was a

scientist, philosopher and banker - an unusual combination. He had been trained as a physicist at Cambridge, was a banker by profession, and a philosopher by inclination.

Whyte listened to the ideas presented to him. He was impressed and was favorably inclined toward the project. He told Whittle he was prepared to recommend financial support for the project provided that an independent engineering assessment was made and that the assessment was favorable.

By whom and how would the assessment be made?

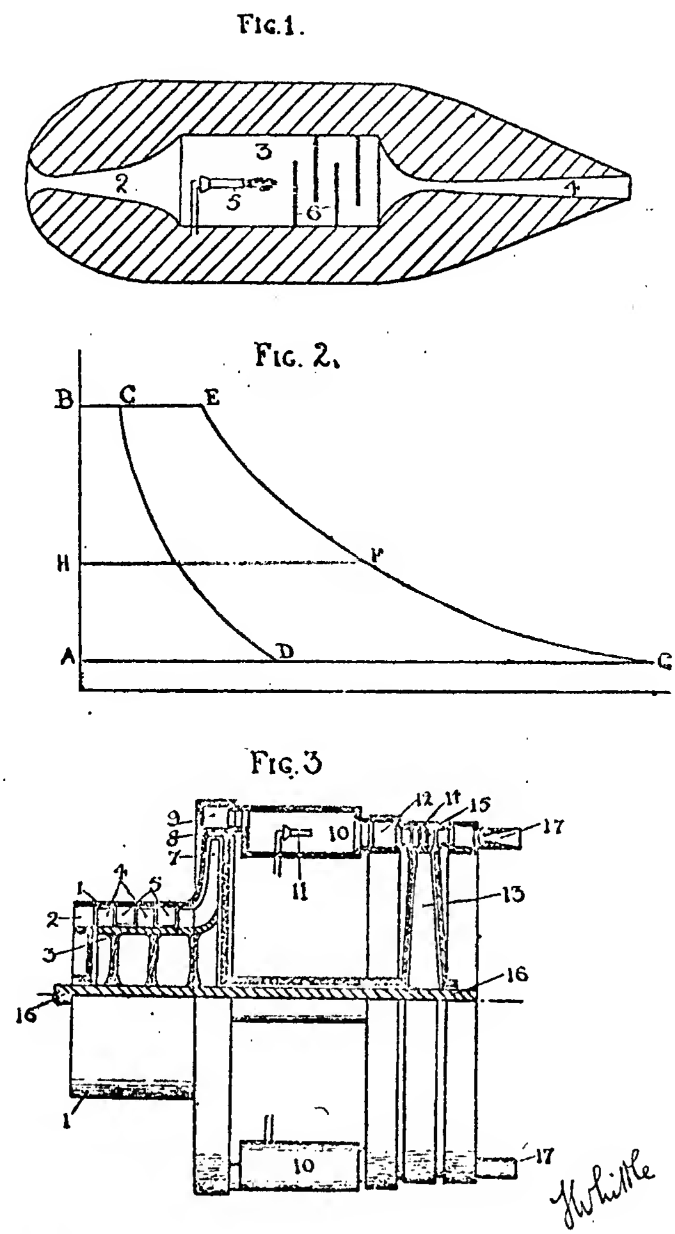

Fig. 1. Reproduction of Drawings Illustrating British Patent No. 347,206, filed 16th January 1930

The upper drawing—the thermo-propulsive duct—had to be deleted from the specification.

EXHIBIT 1

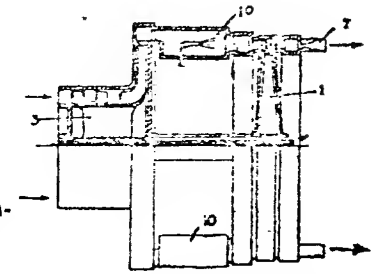

Abb. 14. Whittle 1935. Brennstrahl treibt Kompressor-Gasturbine.

Abb. 14.

Translation

Fig. 14. Whittle 1935. Exhaust Jet Drives a Gas Turbine Compressor

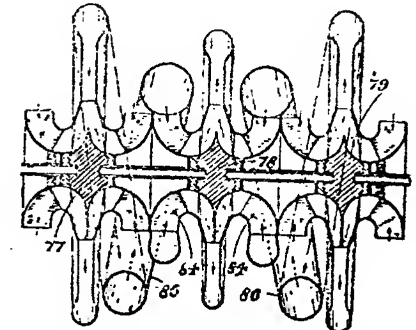

Abb. 65.

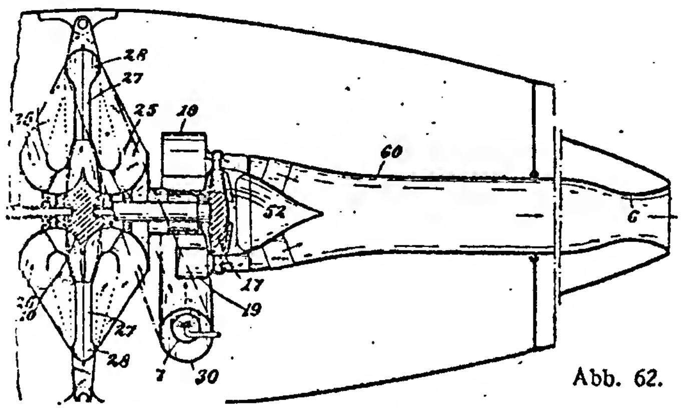

Abb. 62.

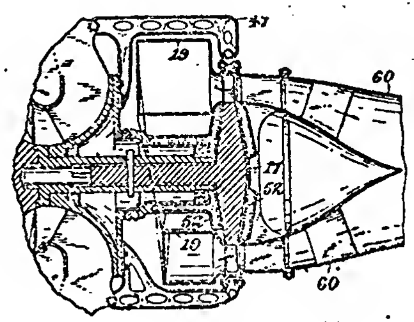

Abb. 63.

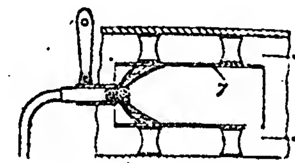

Abb. 64.

Abb. 62—65. Whittle 1935: Heizluftstrahltriebwerk mit Axialturbine.

Translation **Figs. 62–65. Whittle 1935: Thermal Jet Propulsion with Axial Turbine**

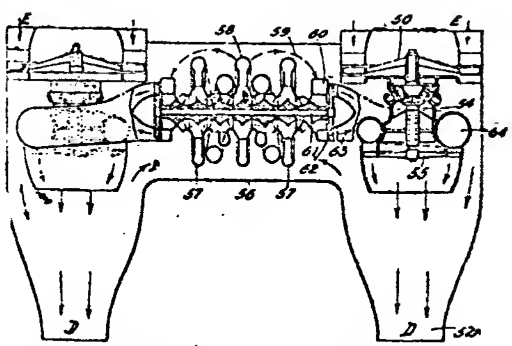

Abb. 66. Whittle 1936: Zwillingstriebwerk.

Translation

ig. 66. Whittle 1936: Twin Propulsion System

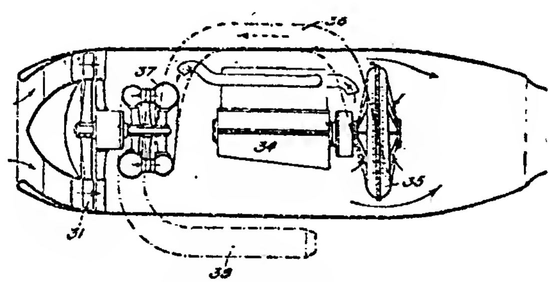

Abb. 67. Whittle 1936: Heizluftstrahltriebwerk mit Kolbenmotor und Turbine.

Translation

Fig. 67. Whittle 1936: Thermal Jet Propulsion with Piston Engine and Turbine

Reproductions of Illustrations from *Flugsport* (1939)

EXHIBIT 2

"THIS MUST BE DONE!" (B)

Whittle, Williams, and Tinling took Whittle's ideas for the development of the turbo-jet engine to M. L. Bramson, a well-known independent aeronautical consulting engineer, who introduced them to Sir Maurice Bonham-Carter and L. L. Whyte of O. T. Falk and Partners. This firm was associated with the investment banking firm of which O. T. Falk and Sir Maurice Bonham-Carter were managing directors. O. T. Falk and Partners handled business which was not suitable for the company, both making certain investments in its own name and also securing additional direct investment by outside capital. Years later M. L. Bramson was to recall that meeting.

"THIS MUST BE DONE!" (B)

BACKGROUND COMMENTS BY THE REPORTING ENGINEER 33 YEARS LATER

In 1935 my practice as a consulting engineer was conducted from an office in Bush House, London, and Flt. Lt. Frank Whittle appeared there one day. He wanted financing for the development of a system of jet propulsion of aircraft, which he had invented. About two years earlier he had submitted it to the British Air Ministry, who had turned it down.

His material consisted solely of thermodynamic and aerodynamic calculations and diagrams; there were no engineering designs.

He was a bright, confident, young officer-pilot in the Royal Air Force, who seemed to know what he was talking about. This impression was somewhat qualified by the eyebrow-raising improbability of his basic thesis that aeroplanes could be made to fly without propellers. Moreover, my own retention of thermodynamic theory was rusty, which made me distrust my own judgment. Nevertheless, or perhaps for this reason, as well as because of my general favourable impression of Whittle, I decided to study his theories and proposals thoroughly. This took two weeks.

At the end of that period I got quite excited. First because of the insight, clarity and accuracy of his presentation and calculations; secondly because my scepticism of any project based on internal combustion turbines (which had hitherto resisted all practical development efforts) disappeared when I realized that here, for the first time, was an application where maximum energy was needed in the turbine exhaust, instead of in the shaft. This was, of course, the reverse of all past objectives for such turbines. And, thirdly, because of the dramatic advance in aviation technology implicit in Whittle's theories.

I suddenly felt "This *must* be done!", (which meant "financed"). A survey of my clients produced a London firm of investment bankers, O. T. Falk and Co., whom I approached. They sent along to see me a man who turned out to be an astonishing professional hybrid, to wit: A financial expert and a theoretical physicist! His name was Lancelot L. Whyte, and thanks to his comprehension and sense of perspective, a favourable decision was made. There was, however, one proviso: An independent engineer's report must be produced and must be conclusive.

When this decision was conveyed to Whittle he said, in effect, "Very well, but Bramson must be that engineer, for it is premature and potentially dangerous (he meant nationally) to spread detailed knowledge of this discovery any farther".

So, instead of my initial role of capital-raising intermediary (entitled to some minor participation) I had, for the good of the cause, to become an ethically-independent (i.e. non-participating) reporting engineer. It pleases me to remember that I did so enthusiastically.

My report was indeed conclusive. And three years later the first Whittle jet engine was tested in Rugby at the British Thomson-Houston Turbine Factory; and the first jet powered aircraft flew in 1941.

Re-reading the report after all these years, I find there are only minor points, of emphasis rather than of substance, that would need amendment. But any temptation to feel smug about that is immediately squelched by one's immense admiration for the originator of one of the most striking and consequential technological revolutions of our time.

M. L. BRAMSON

12th November 1968

Report on the Whittle System of Aircraft Propulsion (Theoretical Stage)—October 1935

M. L. BRAMSON, ACGI, FRAeS

1. TERMS OF REFERENCE

The purpose of this Report is to record the result of an independent step by step check of the theories, calculations and design proposals originated by Flt. Lt. Whittle, and having for their object the achievement of practical stratospheric transport. No investigation of the patent situation has been attempted.

2. MATERIAL SUBMITTED BY FLT. LT. WHITTLE

The inventions and discoveries of Flt. Lt. Whittle have not yet reached the experimental stage, and so the material available for investigation is, necessarily, confined to a reasoned statement of the principles involved, coupled with justifying aerodynamic and thermodynamic calculations and design proposals.

3. DESCRIPTION

A. The Problem

The desirability of stratospheric flight arises from the rapid decrease of air-resistance (drag) experienced at high altitudes, due in turn to the low air densities obtaining there. For example, the density at an altitude of 69 000 ft is only one-sixteenth of normal atmospheric density at sea level. The principal difficulty to be overcome for this purpose is the maintenance of power notwithstanding the rarification of the atmosphere available for combustion. This difficulty has, in a moderate measure, been overcome by supercharging aero-engines of orthodox type, but it can be shown that supercharging to the extent which would be necessary for maintenance of adequate power in the stratosphere would not be feasible on account of the power which would be consumed by such a supercharger even if the size and weight were not prohibitive.

Furthermore, even assuming that means were found to maintain adequate power at the altitude mentioned, the orthodox means, to wit the aircraft propeller, of applying that power effectively to the atmosphere for propulsive purposes would need to be of impracticable dimensions.

Those, briefly, are the reasons underlying the search for some alternative mode of propulsion which shall both maintain and apply propulsive power with adequate efficiency at those altitudes where such power will produce the greatest speed, economy and range.

It has long been recognised that for this purpose some form of jet propulsion would be necessary. Many suggestions have been made to that end, mostly based on the use of some explosive as propellant, but none have been practical. They have failed to provide a solution in the main, either because they involved carrying in the aircraft not only the fuel but also the oxygen required for combustion, or because though theoretically capable of functioning in the stratosphere, the means proposed were incapable of raising the aircraft to the stratosphere.

B. Solution Proposed by Flt. Lt. Whittle

The system of propulsion proposed by Flt. Lt. Whittle falls, and will be treated, under three headings: Aerodynamic principles, Thermodynamic principles and Engineering. The general scheme is as follows:

An aeroplane of the "cleanest" possible aerodynamic form is provided with a circular or annular forward orifice facing the air stream. (*NOTE.* In this report all dimensions, temperatures, pressures and other figures given will, unless otherwise stated, relate to the particular case of an aircraft and reaction engine designed to operate at an altitude of 69 000 ft and at a speed of 500 mph). This orifice communicates directly with what may be termed the engine room in which will exist a pressure exceeding that of the surrounding atmosphere by the pressure head corresponding to the kinetic energy of the airstream meeting the said orifice. The air thus partly compressed is drawn into a centrifugal air compressor which delivers into a heat insulated combustion chamber. Oil fuel is admitted into this combustion chamber where it burns, thus relating the temperature of the air which is allowed to expand at constant pressure in the combustion chamber. The mixture of air and products of combustion then flows to the intake nozzle or nozzles of an impulse turbine so designed that the temperature and pressure drop is only sufficient to enable the turbine to drive the centrifugal compressor to which it is directly coupled. The energy contained in the airstream issuing from the turbine exhaust is thereupon converted into kinetic energy in a propulsion nozzle which delivers a high velocity jet of air and combustion gases through an orifice in the tail of the aeroplane. The total forward thrust imparted to the aeroplane is equal to the force required to accelerate the mass of air flowing through the machine in unit time from rest to the velocity (absolute) of the propulsion jet.

Aerodynamic Principles

When an aeroplane is in steady horizontal flight the force of propulsion must be equal to the total air resistance or drag. For a very clean streamline aeroplane without excrescences such as undercarriages and the like, the drag may, under the most economical flight conditions, amount to one-eighteenth of the total weight of the aeroplane. Such an aeroplane might be designed to have its most economical speed at ground level at, say, 125 mph. Under corresponding flight conditions the speed is, for practical purposes, inversely proportional to the square root of the air density. Therefore, at 69 000 ft, for example, where the relative density is 1/16, the corresponding speed of such an aircraft is $125 \times \sqrt{16} = 500$ mph. At this speed drag will still be the same fraction (1/18) of the total weight of the aeroplane, and if therefore, a thrust of equal amount can be maintained the speed of 500 mph will be achieved. Any excess of thrust available between ground level and the operating altitude can be used for climbing in overcoming the component of gravity which lies along an inclined flight path.

Thermodynamic Principles

The Whittle Reaction Engine is based upon a heat engine cycle of the "combustion at constant pressure" variety. The inventor has prepared pressure-volume diagrams and entropy diagrams, for the particular case of his reaction engine which forms the subject of the critical discussion below. One set of diagrams represent conditions at 500 mph at the

operating height of 69 000 ft, and the other set represents starting conditions at no airspeed and at sea level. These diagrams have been attached as Appendix No. I to this Report (*see* p 132).

The thermodynamic cycle is as follows:- Air at 220°C absolute and 0·702 lb/sq in absolute pressure (Atmospheric conditions at 69 000 feet) is compressed adiabatically (due to the forward speed of the aircraft as mentioned above) to 245°C absolute and 1·04 lb/sq in. It is thereupon further compressed adiabatically in the centrifugal compressor to 6·76 lb/sq in which gives a theoretical temperature increase to 420°C abs. All losses in the compressor (assumed efficiency 80 per cent) with the exception of bearing and radiation losses which are negligible, will be transformed into heat contained in the air so compressed. This produces a further temperature rise from 420°C to 464°C absolute. Heat is then added at constant pressure, (fuel oil is introduced and burnt in the combustion chamber) raising the temperature to 1092°C absolute. Expansion now takes place in two stages: the first stage takes place in the turbine nozzles through which there is a pressure drop from 6·76 lb/sq in to 2·3 lb/sq in, the corresponding theoretical temperature drop being from 1 092°C to 800°C absolute. During this expansion the gases accelerate from 300 ft/s up to a velocity of 2500 ft/s. They thereupon impinge on and pass through the turbine blades, to which, assuming a 75 per cent turbine efficiency, they give up 75 per cent of their kinetic energy. The losses, amounting to 25 per cent of the said kinetic energy, are essentially fluid friction losses, and are therefore transformed into heat which raises the temperature at the turbine exhaust from 800°C absolute to 875°C absolute.

The second expansion stage takes place in the propulsion nozzle, the pressure drop being from 2·3 lb/sq in absolute to 0·702 lb/sq in abs and the corresponding temperature drop from 873° abs to 623° abs. The result of this expansion is that the gases are accelerated to a velocity of 2320 ft/s. The thrust per lb of air per second flowing through the nozzle is given by the formula $(V-u)/g$, where V is the velocity of the jet, u is the speed of the aircraft in ft/s., and g is the acceleration due to gravity. In the particular case under consideration this thrust would therefore be $(2320-733)/32{\cdot}2=49{\cdot}3$ lb per lb of air per second. (*Note*: 500 mph = 733 ft/sec).

Thus in the case of an aeroplane weighing 2000 lb and requiring a thrust of 1/18 of that weight, *i.e.* 111 lb, $111/49{\cdot}3=2{\cdot}25$ lb/s of air will be the necessary capacity of the reaction engine to provide the thrust required.

The interesting case of non-level conditions at no forward speed of the aircraft is dealt with in the inventor's second Pressure-Volume Diagram in Appendix I. The main differences are:-

1. The initial temperature which is 288°C abs instead of 220°C abs.
2. The smaller amount of heat added per lb of air so not to exceed the same maximum temperature of the cycle and the same blade temperature as that adopted for the high altitude conditions.
3. The greatly increased throughput in lb/s of the reaction engine due to the increased density of the atmosphere.
4. The fact that due to the aircraft being stationary, there is only one compression stage.

The net result of these changes in conditions is, it will be seen, that the *thrust per lb of air* per second is slightly greater namely 53·2 lb but the thrust due to the 36 lb/s throughout is $36\times 53{\cdot}2=1915$ lb which is nearly equal to the weight of the aircraft. (Should these figures actually be obtained it is clear that both acceleration and climb will be very rapid.)

Efficiencies

The overall efficiency of a reaction engine of this type is the thrust horse-power divided by the input of heat energy in unit time. (This corresponds to the thermal efficiency of an aero-engine multiplied by the propeller efficiency.)

In the particular case referred to, thermal efficiency (i.e. the kinetic energy given to the working fluid divided by the heat energy input) would be 48 per cent giving an overall efficiency 17·13 per cent. For the sea-level conditions, and assuming a flying speed of 125 mph the thermal efficiency would be 22·9 per cent and the overall efficiency would be 4·5 per cent.

Engineering

The Power Unit

The Whittle Reaction Engine consists of a single-stage turbo-compressor directly coupled to and driven by a gas turbine of the pure impulse type. Taking the case of a unit capable of a throughput of 2·25 lb of air per second at 69 000 ft, the impeller diameter would be 19 in and its speed would be 17 850 rpm giving a linear tip speed of 1470 ft/s. (The overall diameter of the compressor would be 43 in.)

The compressor has a double inlet and its designed capacity would be 470 cu ft/s giving an inlet velocity of 400 ft/s. The turbine may, alternatively, consist of a double row velocity compounded impulse wheel or of two single row impulse wheels working in parallel. The latter arrangement is probably preferable as it permits direct coupling between the compressor and the turbine. (The two row turbine wheels would have to be geared down in relation to the compressor; this complication might, however, be balanced by the advantage of lower peripheral speed of the turbine wheels.) For efficiency, the linear speed of the single row turbine blades should be one half that of the gases issuing from the turbine nozzle (*See* Appendix III) which is 2500 ft/s. The turbine blade speed should therefore be 1250 ft/s and the effective diameter of the turbine wheels 16·15 inches.

The turbine exhaust gases pass straight to the propulsion nozzle where, as already mentioned, the speed of the gases is accelerated to 2320 ft/s. The volume per lb of gas has at this point expanded to 591 cu ft/lb giving a total of $591\times 2{\cdot}25=1330$ cu ft/s in the particular case considered. This gives a propulsion nozzle outlet diameter of 10·25 in.

The Aeroplane

The aeroplane consists of a fuselage of correct streamline form, the forward portion of which is a sealed air reservoir capable of withstanding an internal pressure of 15 lb/sq in and containing the pilot, passengers and controls. An annular opening facing the air-stream is formed between the circumference of this sealed portion and the monocoque shell of the rest of the fuselage. The total cross-sectional area of this annular opening need only be about 100 sq in (in the particular case considered), which, assuming 4 ft 6 in to be the diameter of the sealed portion, gives a width of the annular opening of only 0·6 in. (In actual practice the width of this opening would be made greater to make certain of getting the full necessary flow.)

A cantilever monoplane wing of 52 sq ft area would be fitted giving a wing loading of 19·3 lb/sq ft. As there is no propeller there is no need for large ground clearances during the landing and take-off, and the retractable undercarriage can be short. Furthermore, as the machine is designed and intended for flight at its most economical angle of incidence, the wings can be set at a larger angle of incidence in relation to the fuselage than is the present practice. Thus, even from the point of view of getting correct wing incidence for take-off and landing, a high undercarriage is not necessary. An auxiliary compressor would be fitted drawing air from the

pressure side of the main compressor and delivering at normal atmosphere pressure into the sealed cabin.

The inventor claims that by fitting a correctly designed sleeve of venturi shape over the propulsion nozzle, an increased propulsion efficiency can be obtained, but any such possible advantage has been ignored in his calculations.

4. CRITICAL DISCUSSION

The following critical discussion is based entirely upon the particular case to which reference has already been made and which has been worked out by the inventor. The calculations have been checked. The data are as follows:—

	Given	
Aeroplane	Weight	2000 lb
	Wing loading	19·3 lb/sq ft
	Most economical speed (speed of minimum drag)	125 mph at ground level
	Minimum drag	111 lb
	Corresponding speed at 69 000 ft altitude (where effective efficiency 1/16 is 500 mph)	733 ft/s
Engine Thermal Cycle	Assumed compressor efficiency	80%
	Assumed turbine efficiency ...	75%
	Total theoretical temperature rise due to compression ...	200°C
	Maximum turbine blade temperature	527°C 800°C abs.
	Actual temperature rise due to 1st stage of compression (pitot head)	25°C
	Therefore, rise of temperature due to 2nd stage of compression (compressor)	175°C
	Actual temperature rise in compressor 175/0·8 ...	219°C
	Initial air temperature	220°C abs.
	Temperature after pitot head compression	245°C abs.
	Effective heat drop in turbine	219 units

(*Note* 1. The unit of heat chosen in these calculations is the [illegible] multiplied by the specific heat of air at constant pressure or in other words, the quantity of heat required to raise one pound of air one degree centigrade at constant pressure.)

(*Note* 2. The figure of 219 units is derived from the stipulation that the turbine must be able to drive the compressor.)

Theoretical heat drop in turbine 219/0·75	292 units
Deduced	
Final compression temperature 245°C+ 219°C	464°C abs.
Maximum temperature of cycle 800°C+ 292°C	1092°C abs.
Overall temperature ratio of compression— 420/220	1·91
Temperature ratio of first stage (turbine) of expansion 1092/800	1·366
Therefore temperature ratio of final expansion 1·91/1·366	1·40
Temperature before final expansion 1092—219	873°C abs.
Temperature at end of final expansion 873/1·40	623°C
Therefore useful heat drop is 873°C—623°C	250 units
To obtain the effective output of the engine the heat equivalent of the pitot compression must be deducted	
Therefore effective output of engine= 250–25	225 units
Heat addition = 1092°C—464°C ...	628 units
Therefore thermal efficiency = effective heat drop/heat addition = 225/628 ...	35·8 per cent
The jet velocity resulting from a useful heat drop of 250 units is $146{\cdot}7 \times \sqrt{250}$	2320 ft/s

(*Note.* The constant 146·7 is derived from the mechanical equivalent of the pound calorie).

Hence, net change of gas velocity produced = 2320—733	1587 ft/s
Therefore propulsive thrust per pound of gas per second = 1587/32·2	49·3 lb
Therefore weight of air throughput required per second = 111/49·3	2·25 lb
Propulsive efficiency	48 per cent
Overall efficiency	17·2 per cent
Jet horse-power	308 hp
The thrust horse-power	148 hp

AERODYNAMICS

Flt. Lt. Whittle shows, by the application of Professor Melville Jones' formulae for induced power and profile drag, that a well streamlined aeroplane with the proposed wing loading of 19·3 lb/sq ft may, under conditions of *minimum drag*, be expected to have a lift/drag ratio of 21. He adopts, however, the figure of 18, which more nearly corresponds to flight conditions giving *maximum range*.

There is no serious doubt that an aircraft of the type contemplated could be made to approach the ideal streamline aeroplane as closely as, for example, the modern glider, whose best lift/drag ratio has been known to attain the figure of 23 and over. Flt. Lt. Whittle's figure for drag, and for speed at which such drag will be experienced at 69 000 ft may, therefore, be accepted unreservedly.

THERMODYNAMICS

A Consideration of Basic Assumptions

(a) Compressor Efficiency. The compressor efficiency assumed of 80 per cent is unusually high. There are published test results (ARC R&M 1336) showing adiabatic temperature efficiencies for a single phase centrifugal compressor up to 73 per cent. Dr. A Rateau, probably the greatest authority on exhaust driven turbo-compressors, stated, in an article in the *Revue Génerale des Sciences* of the 15th January 1930 and reproduced in the *Génie Civil* of the 15th February 1930 as follows: (The subject of the article is the supercharging of Diesel Engines by means of exhaust driven turbo-compressors) .....“On the other hand in designing the compressor exactly for the required throughput of air, efficiencies of 82 per cent for the compressor and 78 per cent for the turbine, or in other words, an overall efficiency of 64 per cent can be counted on ....”

The inventor supplies the following interesting information which he has obtained from the compressor experts of the British Thomson-Houston Co. Ltd. This company is said to have obtained compressor efficiencies of 76 per cent and 82 per cent on actual test. Moreover, they have, on the basis of their experience, established a non-dimensional figure of merit for centrifugal compressors according to which Flt. Lt. Whittle's proposed compressor should compare favourably with their best existing examples.

The main features distinguishing the inventor's compressor from normal practice is the high pressure ratio obtained in a single stage and the high volumetric output. The former is almost a natural function of the peripheral impeller speed and should be realised. The latter is obtained mainly by the double

intake arrangement and without adopting excessive intake velocities 400 ft/s. (A blower built by British Thomson-Houston for Messrs Charles Nelson and Company had a maximum intake velocity well in excess of this figure.)

The very large mass flow obtained through the double intake tend towards increased efficiency since the fluid friction losses cannot increase proportionately.

In view of these considerations, I regard an 80 per cent efficiency as a probability, but by no means a certainty. I do feel confident, however, that with skilful design a compressor efficiency between 70 per cent and 75 per cent will be obtained.

(b) Turbine Efficiency. Referring again to the quotation from Dr. Rateau's paper, it will be seen that 73 per cent is given as obtainable in practice. Having regard to the fact that the blade speed adopted approaches one half the gas speed at the turbine nozzle (which is a condition for maximum efficiency), it is probable that 75 per cent will be achieved.

(c) Temperature Rise due to Compressor. For practical purposes adiabatic compression may be assumed with negligible error. The theoretical temperature rise required is 175°C. For a compressor having a sufficient number of vanes to make the peripheral component of the gas speed discharging from the impeller equal to the peripheral speed of the impeller, the relationship between impeller speed and temperature rise is given by $U^2=32\cdot2\times333\times$ the temperature rise, from which can be derived the impeller speed required $U=1380$ ft/s. The inventor's figure is 1470 ft/s which is, therefore, in excess of the speed theoretically required. The actual temperature rise in the compressor $175/0\cdot8=219$°C, is a measure of the actual power required per pound of throughput. Therefore, actual power required equals $(2\cdot25\times333\times219)/550=300$ hp. For adiabatic compression, the pressure ratio equals the (temperature ratio)$^{3\cdot5}$. Therefore, as the overall temperature ratio of compression is $420/220=1\cdot91$, the compression ratio will be $(1\cdot91)^{3\cdot5}=9\cdot6$ (This ratio, of course, includes the pitot compression.) I see no reason why these temperatures and compression ratios should not be obtained in practice.

(d) Turbine Blade temperature. A turbine blade temperature of 800°C absolute (527°C) has been taken as the basis of the turbine design. Since the effective power of the turbine must be equal to the power absorbed by the compressor, it follows that the effective heat drop in the turbine must be equal to the actual temperature rise in the compressor which is 219°C. We therefore have actual heat drop in turbine nozzles $219/0\cdot75=292$ units. So that the blade temperature shall be 800°C abs, the temperature at the beginning of the first expansion stage through the turbine must be $800+292=1092$°C abs. This, therefore, limits the heat addition per pound to $1092-464=628$ units. Herein lies the justification for the assumption, or rather the stipulation, that the blade temperature shall not exceed 800°C abs.

(e) Thrust. All the further thermodynamic deductions enumerated previously, follow directly from the fact that in a heat cycle of the type adopted, the overall compression ratio is equal to the overall expansion ratio. One or two points should be noted in this connection. Great emphasis is rightly laid by the inventor on the fact that almost the entire losses incurred in the turbine are transformed into heat in the gas stream. Whereas in all existing applications of a gas turbine such heat would be entirely lost, this is not the case in the reaction engine, since part of such heat is recovered in the form of additional kinetic energy in the jet. The inventor has made no allowance for fluid friction losses in the propulsion nozzle. These should, however, be very small. They should be provided for by a slight increase in the throughput capacity of the unit.

The performance of the reaction engine for ground level conditions has been obtained on the same basic assumptions. The calculations for horizontal flight conditions are given in Appendix II. It will be seen that although the thermal efficiency is low at ground level, the thrust is exceedingly large in relation to the total weight of the aircraft.

ENGINEERING

The Reaction Engine

The peripheral speed adopted by the inventor for the compressor rotor is 1470 ft/s. This is considerably in excess of existing practice. (I am informed by Flt. Lt. Whittle that the British Thomson-Houston Centrifugal Compressor Design Department are aware of certain cases of speeds of 1250 ft/s.) The speed now proposed involves an increase of stress, all other things being equal, of about 38 per cent. Provided one of the modern high tensile steels are used, I believe that with careful design it will be possible to make an impeller capable of standing up to the peripheral speed proposed. Great care must be taken to avoid the risk of vibration of the impeller blade tips. Much depends upon the skill and care employed in the detail design, and one must attach great importance to the employment for this purpose of all available expert advice. Subject to the foregoing, the engineering features of the compressor should be trouble-free.

Combustion Chamber and Burners

These do not call for special comment and any minor problems arising should yield to ordinary skilful design.

Turbine

As already mentioned previously, the turbine consists of two single-row impulse wheels working in parallel and, in fact, having a common shaft. It will probably be proved desirable to machine the two wheels and their shaft from one solid forging. The turbine blade speed of 1250 ft/s gives rise to a stress at the blade root of about 12·6 tons per sq in, for a blade length of 1·33 in. At the very reasonable blade temperature of 527°C adopted, this stress would give a "creep rate" of 2×10^{-7} inch per inch per hour if the steel used is Kayser Ellison 965, which creep must be allowed for in the design.

The turbine wheel rim will necessarily be considerably hotter than the rest of the wheel and will suffer tangential compression stresses in addition to the stresses caused by the centrifugal tension of the blade. The whole design of the turbine discs and blade root and their method of attachment is a very delicate and important matter, and should be submitted to exports. I do not expect trouble due to heat transmission from the rim to the turbine discs. If a small amount of cool air is allowed to enter the turbine casing near the shaft, it will flow outward while being "sheared" at an exceedingly high rate in the small clearance space between the turbine wheel and the casing. This will effectively prevent excessive temperatures from reaching the shaft and/or the bearings.

It is appropriate here to point out that should detailed consideration of the engineering design problems lead to unexpected difficulties, the alternative of adopting a two row 2-stage impulse wheel is available and would lead to considerably reduced peripheral speed. It would, however, be at the expense of simplicity as such an arrangement would necessitate gearing between the turbine and the impeller shaft. In my view, it is worthwhile going to considerable lengths to avoid such gearing. (Likewise, in the case of the compressor, a 2-stage compression could be resorted to at the expense, however, of increased, but not prohibitive, weight and bulk.)

The design problems and difficulties to be overcome, in their probable order of importance, may be summarised as follows:

1. To make provisions for the combined heat and centrifugal stresses at the turbine blade roots.
2. The design and manufacture of a compressor rotor capable of withstanding the centrifugal and bending loads on the vanes.
3. To guard against turbine blade and compressor blade vibration.
4. Design of main shaft to avoid torsional vibration periods, and to resist gyroscopic couples.

I do not regard any of these problems as insurmountable, but I do consider it possible that they may not all be satisfactorily overcome in the first reaction engine produced.

Weight

The inventor estimates the weight of the complete reaction engine unit as 500 lb. Unless or until designs are available it is impossible to form a reliable opinion on this estimate. This much may, however, be said. The working elements of the engine operate at extremely high velocities, a fact which tends towards decreased size and weight for a given power. The same tendency results from the fact that the working elements are purely rotary as distinct from reciprocating and rotary. Furthermore, the engine has no equivalent to cooling fins, water jackets or radiators, nor has it any airscrew. For these reasons it can be safely assumed that even the first complete engine will not so far exceed weight estimates as to render flight tests impossible or inconclusive.

The Stratospheric Aeroplane

Structurally, the proposed stratospheric aeroplane presents no new problem with the one exception of providing a hermetically sealed cabin with safe and satisfactory doors permitting the crew getting in and out. The problem of flying controls and engine controls to be operated from inside a sealed cabin without having numerous sources of air leakage can be simplified by operating all controls hydraulically. By tapping the pressure side of the compressor, an ample supply of air for breathing is available. It will be noticed that the compression pressure is nearly ½ atmosphere which is ample for most people. An auxiliary booster can, of course, be fitted.

DEGREE OF PERMISSIBLE ERROR IN FUNDAMENTAL ASSUMPTIONS

An investigation has been made with the object of ascertaining the lowest compressor and turbine efficiencies at which stratospheric flight would be possible. The result of this investigation shows that even if both the compressors and the turbine efficiencies were each only 60 per cent, then without raising the turbine blade temperature, a thermal efficiency of 14·2 per cent would still be obtained, and an overall (thrust) efficiency of 9·1 per cent. The principal disadvantages experienced in the event of such low efficiencies being obtained would be first, that the throughput capacity of the unit would have to be approximately doubled and secondly, that at ground level an adequate thrust would only be obtainable by permitting an increase of the turbine blade temperature.

5. SUMMARY

The stratospheric aeroplane and the Whittle Reaction Engine have been described in principle and with particular reference to the case of an aeroplane of 2000 lb all-up-weight capable of a speed of 500 mph at 69 000 ft altitude.

The inventor's calculations for the aforesaid particular case have been checked and the results are discussed critically from the aerodynamic, thermodynamic and engineering points of view. It is shown that although the inventor in some respects goes beyond existing experience, he does not appear to go beyond the temperatures, stresses and speeds that are possible with modern technique and materials.

The author's figures are based on a compressor efficiency of 80 per cent and a turbine efficiency of 75 per cent, the attainment of which is considered probable. Nevertheless, it is considered that if these efficiencies are both 60 per cent, stratospheric flight with the Whittle Reaction Engine would still be possible.

6. CONCLUSIONS

1. Flt Lt. Whittle's theoretical calculations and deductions therefrom are substantially correct.
2. His fundamental discovery is that the gas turbine although very inefficient as a prime mover when power is required in the form of shaft horse-power, can be adequately efficient as an auxiliary to the production of a power jet.
3. Should the discovery be successfully put into practice, the points of superiority over existing aeroplanes would be:
   (*a*) Economical speeds of 500 mph and over.
   (*b*) Probable ranges of 5000 miles and over.
   (*c*) The use of non-volatile fuel.
   (*d*) Freedom from noises and vibration.
4. The proposed development though necessarily speculative as regards time and money required, is so important that it should, if possible, be undertaken.

7. RECOMMENDATIONS

The "Brief Outline of Development Procedure" appended to this Report (Appendix III) has, by request, been prepared by the inventor.

I recommend the adoption of the procedure therein proposed with the proviso that all designs should be submitted to an independent authority on turbine and compressor design before actual construction is undertaken.

M. L. BRAMSON
8th October, 1935

Appendix I, Pressure Volume and Entropy Diagrams, and Appendix III, Brief Outline of Development Procedure High Altitude Engine cannot be located. The Society would be grateful to anyone who could give any indication of them.

APPENDIX II
Flight at Sea Level

Air temperature 15°C	288°C abs.
Aircraft speed 125 mph	182 ft/s
Assumed compressor efficiency	80 per cent
Assumed turbine efficiency	78 per cent
Theoretical temperature rise in compressor	175°C
Actual temperature rise in compressor	175/0·8= 219°C
Temperature rise due to pitot compression	1·5°C
Total temperature rise due to compression	219—1·5= 220·5°C
Actual compression temperature 220·5—288	508·5°C
Temperature ratio (175—1·5—288)/288 ...	1·612
Temperature drop in turbine 219/0·75 ...	292°C
Blade temperature (stipulated)	800°C abs.
Maximum temperature cycle=800°C—292°C	1092°C abs.
Heat addition 1092—508·5	583·5 units
Temperature ratio in turbine 1092/800 ...	1·365
Temperature ratio of final expansion 1·612/1·365	1·181
Exhaust temperature of turbine 1092—219	873°C abs.
Final temperature 973/1·181°C	739°C abs.
Final temperature drop 873—739°C ...	134°C

Therefore jet speed $= 146 \cdot 7 \times \sqrt{134}$ ...	1695 ft/s	Thermal efficiency $= 134/583 \cdot 5$	22·9 per cent
Thrust $= (1695 - 182)/32 \cdot 2$	47·0 lb per lb of air	Propulsive efficiency	19·4 per cent
		Overall efficiency	4·45 per cent
Capacity of compressor $= 16 \times 2 \cdot 25$ ...	36 lb/s	Jet horse-power	2880 hp
Total thrust $= 38 \times 47$	1690 lb	Thrust horse-power	561 hp

COMMENT

We consider the publication of the Report to be of importance for four reasons:

(1) It was on the basis of Mr. Mogens Louis Bramson's favourable judgment, as Consulting Engineer, formed against much adverse expert opinion, that the development of the jet engine was originally financed and organised. The Report, which was directed to the original Whittle proposals and the analyses which he had made, was commissioned by one of the signatories (L. L. W.) on behalf of Falk and Partners (O. T. Falk and Sir Maurice Bonham Carter). Together with them, Whittle's friends Messrs. Williams and Tinling adopted the Bramson Report, and so Power Jets Limited came into being.

(2) The Report, as will be seen, is a model of clear and consistent writing and as such deserves to be studied by all technical people whose duties involve reporting. It is remarkable in content, and exemplary in style.

(3) Mr. Bramson, has never, in our opinion received the credit due to him as one of the constructive early proponents: he remained as an actively participating Consultant to the project for several years.

(4) It has been insufficiently recognised that the Whittle project essentially depended on the marriage of a jet engine with a new subgenus of airframe, and that the boldness and completeness of the total concept (as appreciated by Bramson) went beyond the mere proposal of using a gas turbine to produce a propulsive jet. The third signatory (W. E. P. J.) spent many hours with Frank Whittle (whose patent agent he was) discussing the inventive features thus involved, such as boundary-layer control, cabin-pressurisation, bypass-engine feasibility, and the then revolutionary idea of a squat undercarriage.

It is with pleasure that the three signatories below, all intimately connected with the earliest phase of the jet development, have submitted the Report for publication.

FRANK WHITTLE *(Hon. Fellow)*

LANCELOT LAW WHYTE

W. E. P. JOHNSON *(Fellow)*

As a result of M. L. Bramson's favorable report, Falk & Partners were prepared to invest in the development of the turbo-jet engine. Late in 1935 a four-party agreement was drawn up creating a new company called Power Jet Ltd. The Air Ministry had examined Whittle's proposal and declared that it was unlikely that the engine would ever be of military use and that there was no need to impose secrecy; it accordingly granted the commercial and foreign rights in the patents to Whittle, who transferred them to Power Jet. The Air Ministry retained free use of the patents and required that the President of the Air Council be a part of the four-party agreement.

Whittle was in his final year in his mechanical engineering studies at Cambridge. The Ministry gave him permission to devote six hours a week to the affairs of the new company.

Falk & Partners were to invest £2,000 ($10,000) immediately with an eventual capitalization of £10,000 ($50,000). Power Jet was to undertake development of the turbo-jet to Whittle's design.

Thus was set in motion the development of the turbo-jet engine which was to culminate in the first flight of a British jet propelled aircraft in May 1941. The development was to sap the strength of Frank Whittle, and to sorely try the relationships between Power Jet, government agencies, and British industry.

By the time the engine was flying the development had cost the British government £1,300,000 ($6,500,000) and had established Rolls-Royce as a world leader in turbo-jet design and manufacture.

ACKNOWLEDGEMENTS:

1. The events leading to the invention of the turbo-jet and its developments are based largely on Sir Frank Whittle's autobiography "Jet", published by Frederick Muller Ltd., London. The reader is directed to this source for a more complete description of the events and subsequent developments.

2. The Bramson Report is reproduced by kind permission of the Royal Aeronautical Society where it first appeared in their February 1970 Aeronautical Journal, and by permission of the author, Mr. M. L. Bramson.

3. "The Early History of the Whittle Jet Propulsion Gas Turbine" by Frank Whittle, (First James Clayton Lecture) Institute of Mechanical Engineers, London, Proceedings 152, 1945, pp. 419-435. -A technical description of the development of the turbo-jet engine.

4. "Development of Aircraft Engines" by Schlaifer and Heron, Harvard Press, Chapters XII and XIII. -A political, economic study of the turbo-jet engine development.